J. R. OPPENHEIMER

Cosmic Rays: Report of Recent Progress, 1936-1941

THE ORIGIN of cosmic rays has been the subject of a good deal of speculation. The extraterrestrial character of their origin, which has been certainly established for over twenty years, and the rapidly unfolding evidence that the radiation itself has properties qualitatively unlike that of any radiation we can produce in the laboratory, have naturally led to quite radical suggestions about the ultimate source of the radiation. These speculations have been in large part barren because they have been based on theories subsequently shown to be erroneous, of just what the primary cosmic rays—those striking the atmosphere of the earth—really were. Our ideas on this question have undergone many serious revisions in recent years, and it does not seem likely that we have arrived at a final answer even now. But a few facts, clearly established, do serve to exclude some possibilities for the origin of the radiation, and to lend weight to others. Thus it is known that the greatest part, and probably the whole, of cosmic radiation reaches the earth's atmosphere in the form of singly charged particles, and that this charge is largely, if not entirely, positive in sign. The mean energy of the primary cosmic rays is some ten billion electron volts. The minimum energy is some two billion volts, and the distribution in energy appears to be continuously decreasing. But unambiguous evidence shows that there are some primary rays with energies exceeding 10^{15}-electron volts, although rays with this energy are extremely rare, of the order of one in a billion of the total number. These energies so greatly exceed, in order of magnitude, not only those currently released in laboratory experience of nuclear reactions, but the total energy available from the complete annihilation of the heaviest known nuclei, that we may be quite sure that the origin of cosmic rays is not in any way associated with the conversion of matter into energy, or with the phenomena of nuclear physics generally. The view which at present seems most plausible to physicists is that the primary cosmic rays receive their high energies—and on this property alone most of their remarkable behavior would seem to rest—by acceleration in electric fields probably of low intensity but of immense extent. Whether these fields act within stellar systems, or between galaxies, is not established. The actual origin of the radiations thus constitutes a serious and interesting problem for astrophysics, and possibly for cosmology; it probably has no close connection with atomic physics.

What does concern atomic physics—and what for most physicists constitutes the extraordinary interest and puzzle of the cosmic rays—is the behavior of the radiation once it has reached the earth and comes into interaction with the matter of the earth's atmosphere and, later, of the earth's surface; for the cosmic rays give us by far the most powerful high-voltage laboratory that we have, with the primary rays, and some of their secondary products, as the high-energy radiation, and the matter they hit on earth as the target. Even the humblest cosmic ray is, from this point of view, a far more powerful projectile than any we can produce in the laboratory, since it carries some thousand times higher energy than the best products of the cyclotron or betatron.

It may not at first be clear why these high energies are of such interest to the physicist. The reason why high-voltage equipment was necessary to open up the vast field of nuclear reactions was that charged particles are strongly repelled by nuclei and must be given energy enough to overcome this repulsion if they are to penetrate to the nuclear matter and cause transmutation. But the energies necessary for this are well within the range of existing laboratory installations, and in fact all nuclei have been transmuted by cyclotron bombardment. The importance of the vastly higher energies of cosmic radiation to deepened physical investigation lies in a different circumstance. It is this: in a collision in which two particles are hurled together with a momentum p, and energy E, not all features in the interaction will manifest themselves clearly—those whose scale of length is smaller than h/p, or whose scale of time is much shorter than hc/E, will be largely lost because of the inevitable lack of spatiotemporal definition demanded by the uncertainty principle for systems with well-defined momentum. In these formulae *h* is Planck's constant, *c* the velocity of light; their numerical values are such that the characteristic lengths and times for a ten-million-volt electron are about 5×10^{-12} cm. or some ten times nuclear dimensions, and 2×10^{-22} sec., respectively. These spatiotemporal dimensions are decreased roughly in the inverse ratio of the energy with which the collision takes place. Thus, with respect to fundamental physical discovery the domain of very high energies is also the domain of the very small and very rapid—a domain that, as experience has shown, is rich in new complexities and new order. And it is because cosmic rays are unique in opening up this remarkable, strange, and otherwise inaccessible region of the atomic world that they have commanded such interest from physicists.

It is in this connection important, especially in evaluating the rather fragmentary and extraordinarily incomplete knowledge that cosmic-ray experience has given us, to remember that the radiation itself does not have those features of controllability that make an artificially produced laboratory radiation so useful. Work with cosmic rays is necessarily observational rather than experimental. We can alter the nature of the matter which the cosmic rays strike, we can investigate the radiation at various stages in its course through the earth's atmosphere and the earth itself, and we can improve and refine the methods of observation; but we cannot alter the radiation itself, cannot increase its intensity to pursue weak effects, cannot readily separate one component of its complex spectrum from another. These limitations are reflected in our very partial and uncertain knowledge. It is, in its field, the only knowledge we have at all.

This complexity of the cosmic radiation to which I have just referred has made it helpful, in disentangling the phenomena, to distinguish three qualitatively distinct, though genetically related, types of radiation: the soft or cascade component, the mesotrons, and the primary rays. In summarizing some of the remarkable discoveries of recent years, we may follow this classification, although we may be fairly sure that it is a very rough and incomplete one, and postpone our discussion of the genetic relations of these components to the end.

Cascades.—The cosmic rays are very penetrating: it takes some 30 meters of water to reduce their intensity at sea level to one-half, and the radiation is still detectable at 1,000 m of water below sea level. Nevertheless, there is always a portion of the radiation, amounting to more than half at high altitudes, dropping to some 10 per cent just below sea level, and rising again with increasing depth to some 20 or 30 per cent, that is readily absorbed by some inches of a heavy material such as lead. This portion is called the soft component, and the processes involved in its absorption and regeneration have been the subject of a great deal of study. It consists of electrons, which are normal ingredients of matter, and positrons, unstable mates of the electron of the same mass and opposite charge, and gamma rays, high-frequency electromagnetic radiation.

It has taken research and discovery to make this identification, since the positron itself was not known until it was discovered in the cosmic rays, and since the properties of all these radiations are qualitatively unlike anything that was known before. In this development theoretical ideas have played a very great part. Thus the existence of the positron and its properties had been suggested on theoretical grounds before its actual discovery, and this rendered its identification relatively easy and conclusive. The reason for the theoretical prediction of the positron was this: when we try to make a theory of the wave mechanics of electrons which is in accordance with the special principle of relativity, we are led—by very general and inescapable arguments—to the conclusion that the electron must have a mate which is either a particle of the same charge as an electron and of negative mass, or a particle of the same mass and of opposite charge. With the former alternative, ordinary electrons should be able by emission of radiation to transform themselves into electrons of negative mass—the "donkey" electrons, so called because they retreat when we pull, advance when we push them. This prediction, which is in the grossest kind of contradiction with the experimental stability of electrons, shows that of the two alternatives only the second is possible, and that we must have, in nature, particles of the same mass as the electron, but positively charged. A further general consequence of the relativistic wave mechanics is, then, that a pair of positively and negatively charged electrons—a positron-electron pair—may be created by the collision of two sufficiently energetic beams of radiation, or, and this is the case of practical importance, by the impact of radiation on a strong electrostatic field, such as surrounds the atomic nucleus of elements of high atomic number. All these predictions could be made quantitative by assuming the detailed correctness of Dirac's electron theory, which alone had given a complete and experimentally verified account of the properties of electrons in atomic physics, of the electron spin and magnetic moment, and of the duplexity phenomena of spectroscopy. When Anderson found in the cosmic radiation a particle of positive charge and electronic mass, a whole host of experiments soon proved that these positrons could be annihilated, together with an electron, on collision; that such pairs could be made by irradiating heavy elements with gamma rays; and that our quantitative formulae for the probability of these processes agreed with the facts. These phenomena of pair formation and annihilation, which can be studied in the laboratory, since the energy necessary for pair creation is just over one million electron volts, afforded a most striking confirmation of the interconvertibility of matter and energy, in that the energy of a gamma ray could be used up to create the mass of a pair of particles, and conversely in that the mass of a pair of particles could disappear in the form of radiation. The instability of the positron is then naturally ascribed to the circumstance that there is in normal matter a great excess of electrons with which any stray positron will in a short time combine. Positrons of high energy will almost always lose their energy before combining with electrons.

The phenomenon of pair production by gamma rays provides one of the two essential mechanisms dominating the behavior of the soft component. The probability that a gamma ray of high energy (above some ten million volts) will make a pair on hitting the strong electric field around an atomic nucleus is proportional to the square of the nuclear charge, and independent of the gamma-ray energy. Thus the penetrating power of gamma rays is limited, whatever their energy, and is much smaller in heavy materials than in light. The mean distance that a gamma ray travels before making a pair is, in Pb (lead), about 0.6 cm; in water, about 50 cm. It is, then, clear that a few inches of Pb will absorb all the incident gamma radiation.

In order to follow the behavior of the soft component in detail, it is necessary to know, too, what happens to the high-energy pairs.

Like all charged particles, these lose energy continuously to the loosely bound electrons of the atoms near which they pass, and this loss manifests itself in ionization of the atoms and thus affords the actual means of detection in ionization chambers, counters, and cloud chambers of the cosmic rays. But electrons and positrons also lose energy by another, and for high energies incomparably more important, mechanism. When they pass through the strong electric fields around atomic nuclei—the same fields in which gamma rays produce pairs—they are deflected, accelerated, and radiate. Here again the probability of radiating as gamma radiation a given fraction of the electron's energy is independent, for high energies, of the electron's energy, and proportional again to the square of the atomic number of the material; and the characteristic distance in which an electron will, on the average, have lost half its energy in the form of radiation is slightly smaller than, though of the same order as, the characteristic absorption distance for gamma rays, amounting to 0.5 cm of Pb, 40 cm of water.

What, then, do these theoretical predictions imply, for the behavior of an electron, positron, or gamma ray of very high energy incident on matter? In a very short distance the gamma ray will make a pair; the pair will make gamma rays; the gamma rays will make further pairs, and the pairs further gamma rays, and all these secondary radiations will be just about as penetrating and absorbable as the primary. Thus, from one initial energetic ray we shall soon have built up a great shower or cascade of rays, and this multiplication will continue until the rays are of such low energy that they are no longer effective in radiating and producing pairs, and lose their energy by ionization alone. The characteristic energy at which multiplication ceases is lower in heavy elements than in light, since in the former the multiplicative processes are more probable. The energy is about 9 mev (million electron volts) for Pb, about 100 mev for water. For this reason the multiplication proceeds further, and for a given total energy leads to a larger cascade in heavy elements than in light. A 10^{10} v-electron will in Pb make a shower in which at the maximum—and this occurs some 3 cm from the surface—there are about 100 charged particles and some 150 gamma rays; a 10^{15} v-electron will make a shower of some 5,000,000 particles, reaching its maximum dimension after some 8 cm of Pb, some 6 m of water. Almost all the secondary radiation preserves approximately the primary direction, with appreciable angular deviations limited to secondaries of low energy.

This, then, is what atomic theory says about the behavior of the soft component. For a long time these ideas—which only recently have been worked out with full mathematical elaboration—were viewed with a good deal of skepticism, for three reasons:

1. If these ideas are right, electrons, positrons, gamma rays, are all very rapidly absorbed; 20 cm of Pb should take out even the most energetic soft radiation. Yet the cosmic rays are penetrating, and even a meter of Pb does not reduce their intensity by a factor of 2.

2. Direct cloud-chamber observation of the behavior of cosmic rays, at sea level, showed that the overwhelming majority would pass through a plate of Pb without undergoing the energy loss, or manifesting the multiplication, theoretically predicted for electrons.

3. Although phenomena of shower formation have long been known, and have been studied by coincidence-counter, ionization-chamber, and cloud-chamber techniques, it was for a long time erroneously believed that these showers were explosive, many rays being simultaneously created in one collision process; and only a detailed analysis revealed that the overwhelming majority of showers were in fact multiplicative, and that the explosive events were rare and of a characteristically different nature and distribution.

Arguments 1 and 2 had an added cogency since it was quite easy to show that the penetrating cosmic rays most certainly were not protons or other nuclei, in that their mass was smaller than the proton mass and they occurred with about equal frequency with positive and with negative charge. The acceptance of the theoretical ideas concerning the behavior of the soft component therefore brought with it the necessity of admitting that the penetrating, and at sea level the preponderant, component of cosmic rays consisted almost wholly of radiation not hitherto known to physics. The evidence of the detailed agreement between the actual behavior of the soft component, in its shower formation, multiplication, and absorption, and in the location of the shower maxima and the dependence of this on material and on shower size, left in the end no doubt that the theoretical predictions were right, and that the soft component of cosmic rays was only a part of a far more complex radiation, of which the greater part was not electronic, and was new. The positive and negative particles of this penetrating radiation, identified at first only in the negative sense that they were neither electrons, positrons, protons, nor any known particle, have come to be known as mesotrons, or mesons, because their mass is intermediate between that of electrons and that of protons. The mesotron also, like the positron, had been the subject of theoretical speculation before it was discovered. But before we enter on the arguments involved, and the difficult and as yet unsettled question of the range of their validity, it will be well to sketch one other important application of the cascade theory of the soft component, an application which was for long regarded as its greatest success, but which we now know to be in large measure illusory.

This has to do with the course of cosmic rays incident on the earth's atmosphere. To simplify and render quantitative the argument we may confine our attention to those rays which reach the earth at a high geomagnetic latitude but not near the equator. These rays are charged particles having energy sufficient to penetrate the geomagnetic field of the earth at high latitudes but insufficient to penetrate in the equatorial belt. By choosing two suitable latitudes it is thus possible by subtraction of the low-latitude from the high-latitude effects to obtain the effects which must be ascribed to primary charged particles lying in a relatively narrow and accurately calculable energy range. If the ionization due to these primaries, lying for example in the range 10–15 bev (billion electron volts), or the frequency of counting, in a vertical counter telescope, is plotted against the amount of matter traversed by the radiation from the top of the earth's atmosphere, a curve is obtained which at first rises steeply, has a sharp maximum at about 100 gm/cm^2, and then falls off rapidly at greater depths. This curve is in rough but excellent agreement with the theoretically calculated cascade curve for the behavior of a 12-bev electron or positron incident on the earth's atmosphere: the position of the maximum agrees precisely with that calculated, and there are only two, obviously related, points of discrepancy. One is that the maximum reached—about 10 particles per primary in this case—is about 30 per cent below the theoretical; the other is that the curve at great depths, near sea level (1,000 gm/cm^2), falls off much less rapidly than the cascade curve. This last is just another expression for the fact that if all cosmic radiation were soft we could not account for its actual very great penetration. It was, then, natural to suggest that the primary and secondary cascade radiation could in part be converted, on nuclear impact, into mesotrons; that this at the same time reduced the extent of the cascade multiplication, by converting a part of the energy into nonmultiplying components, and accounted for the low absorption at great depths. The probabilities estimated in this way for mesotron production seemed, in the light of theoretical speculation, not unreasonable, and the good agreement between cascade theory and atmospheric "transition" curves was taken as at the same time validating the cascade theory and establishing unambiguously the nature of primary cosmic radiation: since it was charged, and predominantly, at least, positively charged, and produced showers, it consisted of positrons. Cosmologically this was an odd result, since the only processes we know that make positrons also make gamma rays and electrons. But these worries turned out to be unnecessary: the multiplication of primary cosmic rays in the upper atmosphere, which seemed to be described so well by the cascade theory, now appears to be a totally different and even more remarkable phenomenon. To this we shall return in our last section.

Mesons and Nuclei.—The suggestion that there exist particles carrying a unit positive or negative charge and with a mass approximately two hundred times that of the electron and approximately one-tenth that of the proton, was first put forward by Yukawa about three years before it was generally recognized by physicists that such particles constituted the penetrating component of cosmic rays. Yukawa's arguments were a great deal more speculative than those on which the prediction of the positron was based; and although mesotrons are now known to exist, and are in fact known to have not only the mass and charge Yukawa predicted, but also to be, as he suggested, unstable (with a half life of some microseconds), nevertheless it is now quite certain that the mesotron will not perform that function for which Yukawa invented it, namely, to give us a direct consistent theory, in agreement with known facts, about nuclear forces. The situation in this respect is not only rather complicated; it is also very incompletely understood, and presents at the moment the principal challenge to theoretical physics.

It will be helpful to outline first Yukawa's ideas, and then the facts that bear on them, and finally the present dark state of the theory.

Yukawa put forward a theory of nuclear forces based on an analogy *con variazione* with the Faraday-Maxwell field theory of electromagnetic interactions: he tried to make a theory in which the forces between neutrons and protons, protons and protons, neutrons and neutrons, appear not directly in terms of action at a distance, but through the intermediary of a field: each neutron and proton (we call them nucleons) produces a field, and another nucleon moving in that field is subject to forces. In electrodynamics this formulation has proved powerful and led to increased insight, in that the laws for producing electromagnetic fields, on the one hand, and the response of charges to such fields, on the other, are far simpler than the actual laws of interaction of charges. Field theories of this type also automatically satisfy the fundamental requirement of the special theory of relativity, that momentum and energy be propagated with a finite velocity, never exceeding that of light. Since our empirical knowledge of nuclear forces has not led to any great insight into their detailed nature, it was natural to look to field theories to provide us with a powerful method of investigating them.

The two points in which nuclear forces differ most strikingly from electromagnetic forces are that they have a very limited range, $R \sim 10^{-13}$ cm, and are very much stronger than electromagnetic interactions between elementary particles. Yukawa was now able to establish the following general important interpretation of the range R. Just as the quantum theory leads to the existence of light quanta, or photons, which carry the energy and momentum of the electromagnetic field, so, in general, quantum theory will ascribe corpuscular properties to any field. Yukawa could now show that if these quanta had a mass $M = h/Rc$, then the range of forces would be of the order R. With the best values for R, obtained from evidence on nuclear forces, M turns out to be approximately two hundred electron masses, very close indeed to the best experimental determinations of the mass of the mesotron, the penetrating particle of the cosmic ray.

By rather less general arguments, Yukawa, and others working on the elaboration of this theory, were led to assign further properties to these nuclear force quanta, or mesons as we call them.

1. From the striking saturation character of nuclear forces—that is, from the fact that the density of nuclear matter is about constant for all nuclei, as is also the binding energy per nucleon—physicists had concluded that the exchange of momentum between nucleons, which gives the forces between them, is often if not always accompanied by an exchange of charge. This leads to forces of the so-called exchange type, which have saturation properties similar to the familiar ones that characterize the homopolar chemical bond. For this reason Yukawa assumed that mesons carried a charge—an elementary positive or negative charge. The question of the existence of neutral mesons is not yet definitively settled, and the cosmic rays do not provide any good grounds for believing in them. The cosmic-ray mesons are singly, positively and negatively, charged.

2. Yukawa suggested that mesons are spontaneously beta-radioactive, and estimated their lifetime on the assumption that it is their presence in nuclei which give rise to the observed beta and positron radioactivity of nuclei. Although efforts to refine the quantitative connection between beta decay and meson decay in nuclei have not been successful, the general order of magnitude of the lifetime of the meson, predicted by Yukawa as a microsecond, is in good agreement with the best cosmic-ray observations. These observations are themselves of interest. They rest on a circumstance long ago noted, that the absorption of cosmic rays in the atmosphere exceeds their absorption in an equivalent weight of any kind of condensed matter. By assuming that this excess absorption is to be ascribed to the spontaneous decay of mesons in their relatively long paths through the rare atmosphere, and by taking into account the Einstein effect, or retarding of the decay process for fast-moving mesons, one can obtain a reasonably consistent interpretation of all the absorption data by assigning to a meson a proper lifetime of some microseconds. An extremely important consequence of this result is that mesons are not primary: they are themselves produced in the earth's atmosphere by the primary rays. The view that they are produced by nuclear impacts is of course in qualitative agreement with Yukawa's theory, according to which mesons are present in the field of all nuclear particles.

3. Nuclear forces are strongly spin-dependent, that is, they depend strongly in magnitude, and even in sign, on the relative orientations of

the intrinsic spins or angular momenta of the nucleons involved, and the orientation of these spins with respect to the line of centers of the nucleons. To explain this dependence, Yukawa and others assumed that the meson, like the photon, had itself a unit of angular momentum or spin, which it could carry from one nucleon to another. It turned out that this assumption was not necessary to explain the spin dependence of nuclear forces; and in fact an analysis of the collisions of mesons with the electrostatic fields surrounding nuclei, in which they, too, like electrons, can radiate gamma rays—gamma rays which, if of sufficient energy, are readily detectable as large cascade showers or bursts,—showed unambiguously that the meson spin is not unity, that it may be zero, or, as it is for the electron, ½. The value 0 is alone consistent with Yukawa's field theory in its simpler forms.

4. A final known essential difference between meson and photon fields is that the meson fields are near nucleons, and correspondingly the strength of nuclear forces is enormously greater than in the electromagnetic case. For the mathematical treatment of this case quite new methods have had to be worked out, the physical content of which lies in treating the nucleon plus its intense field, rather than the "bare" nucleon, as the fundamental particle. One of the most interesting qualitative predictions of this strong-coupling treatment, as yet unverified by cosmic-ray observation, is the existence of excited states, or isobars, of proton and neutron, with a mass less than 10 per cent greater than that of the known stable forms, and carrying anomalous charges and spins, charges of +2 or −1 units for instance. These isobars are unstable, and only in cosmic-ray phenomena or with a giant cyclotron should we expect to find them.

The quantitative development of Yukawa's ideas along the lines here outlined has not led to a satisfactory theory. In fact, even if we limit ourselves to a consideration of the detailed form of the nuclear forces theoretically predicted, it has not been possible to obtain any measure of agreement, despite the considerable flexibility of these theories, with nuclear experience; nor has it been possible on any of these theories to escape the conclusion that there is a connection between the effective range R of nuclear forces, which is roughly known, and the scattering of mesons by nuclei. The experimental estimates of this scattering systematically fall below the theoretical predictions by a factor of about

100. It is not at present understood how to resolve this difficulty, which has appeared in the detailed elaboration of all forms of meson theory of nuclear forces. Nor has the meson theory of forces as yet helped in any way to systematize or illuminate the facts of nuclear physics. It would seem likely that the source of all these troubles, which so far no amount of mathematical ingenuity has been able to resolve, lies in the inapplicability of field theory to nuclear problems, where the range of forces between nucleons probably does not exceed appreciably the size of the nucleons themselves, and where therefore the Faraday-Maxwell ideas of the propagation of disturbances between small elementary charges, over distances vastly greater than the size of the charges themselves, no longer may appropriately be applied. The problems put to us by this frustration of Yukawa's program would appear to be among the most urgent and deep-seated in contemporary atomic physics. It is important, in this connection, to observe that cosmic-ray findings on the scattering of mesons as well as on their secondary origin, on the nature of the radiative collisions of mesons, and on their shower-producing properties, have served to eliminate many theoretically possible forms of meson theory.

Primary and Secondary Radiations.—Under these circumstances it is inevitable that many physicists should wish to regard the agreement between the properties of the cosmic-ray mesons and the particle predicted by Yukawa as sheer accident, and to revert to the view that mesons have no deep connection with nuclei. It does not seem to us that this is a tenable position: it is not the idea that mesons are essential ingredients of nuclei, responsible for the forces holding them together as well as for many of the properties of the neutron and proton themselves, that is at fault, but rather our mathemaitcal methods and physical models for describing this situation. For mesons most certainly are an ingredient of nuclei, and for this there is direct cosmic-ray evidence of the most striking sort.

We have seen that mesons are secondary cosmic rays, made in the upper atmosphere. Our discussion of the atmospheric transition curve on the basis of cascade theory led us to believe that the primary cosmic rays were positrons, and that either these, or the secondary gamma rays of the cascade, would, in addition to making the great atmospheric cascade phenomena, produce mesons.

Three sets of observations, carried out very near the top of the atmosphere, have shown that this is not so.

1. At less than one cascade unit from the top of the atmosphere, where, according to cascade theory, the number of vertical rays should exceed the number of primary rays by only some 30 per cent, the actual observed number of vertical rays is some five to ten times the number of primaries (these figures refer to the most energetic component; for lower energies the multiplication at this point is two- to fivefold). This indicates that the fundamental multiplicative process has nothing to do with cascades, and strongly suggests that it involves, not the successive building up of the radiation, but the production of a considerable number of secondaries in one elementary collision taking place very near the top of the atmosphere.

2. If the primary radiation were cascade (positrons), then very large showers should be very frequent near the top of the atmosphere. This is not the case. The maximum in the shower component falls well below the maximum in the atmospheric transition curve, and the number of large showers, with an energy of 10^{10} v or so, is far too small to be consistent with the view that primary cosmic rays are positrons of mean energy in this range.

3. If the primary radiation were cascade radiation, most of it, near the top of the atmosphere, before meson production is appreciable, would be absorbed by some inches of Pb. This is not the case; the intensity of radiation, well above the atmospheric transition maximum, is nearly independent of Pb filtration.

These facts show clearly that there is a rapid noncascade multiplication of the primary rays in the atmosphere, and that the immediate products of this multiplication are penetrating cosmic rays, or mesons—whether they are in all respects similar to the mesons which survive at sea level is not known with certainty. A detailed analysis of this primary multiplication shows that it occurs on the average at a depth of some 30 gm/cm^2 of matter, and that the mean number of rays produced in one multiplicative collision is about ten, increasing somewhat with the energy of the primary rays. These fundamental explosions, which occur very much less frequently lower in the atmosphere, but can still be seen in cloud chambers operated at 14,000 ft, and indirectly detected even lower, involve the simultaneous ejection from an atomic nucleus—a nitrogen nucleus for the most part—of some 5 to 20 mesons, together with a general pulverization of the nucleus itself into its component nucleons. This fact alone shows that mesons do play an essential part in nuclei, and confirms in a qualitative way the enormously high meson density around nucleons.

The agreement, then, between the position and magnitude of the atmospheric transition curve and the cascade theory turns out to be an accident: the primary radiation is certainly not cascade. The most conservative hypothesis at the moment is that this primary radiation consists largely of protons (we know it is for the most part singly positively charged). But this is a conjecture only, rendered plausible by the fact that we might expect a collision of one nucleon of high energy with an atomic nucleus to give rise to just such an explosion of mesons as is found.

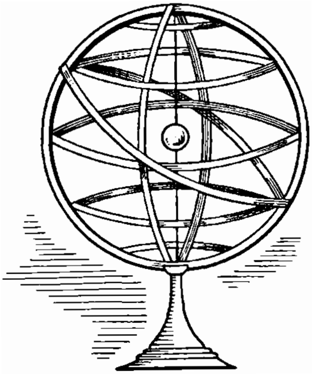
It turns out that many of the mesons so formed are quite slow, and that, traveling in the rare reaches of the upper atmosphere, most of them decay spontaneously, thus giving rise to secondary radiation of rather low-energy electrons and positrons, which subsequently build up small showers and provide a cascade component that is relatively intense in the upper atmosphere. Some part of the meson energy of the penetrating component is converted into the cascade component even in solid matter, where meson decay is insignificant. This is a simple effect, for the most part, in which mesons hit electrons present in matter and give them a high energy. In addition to this, mesons do occasionally radiate in the strong electric fields near atomic nuclei, and this gamma radiation can initiate showers. In this way it is possible to understand fairly well the production and intensity of the soft radiation, not only in the atmosphere, but deep in the earth. The soft radiation, once formed, is adequately described by the cascade theory. But it is almost all tertiary radiation, produced by the decay and the collisions of mesons that are themselves secondary. There is no evidence that mesons, once formed, interact strongly with atomic nuclei, or even that they are scattered by them. I have already mentioned the difficulty of understanding this small scattering.

There is one part of the soft component, insignificant in intensity but unmistakable in its surprising properties, that cannot at present be accounted for as tertiary radiation: this is the showers of immense size that were discovered by Auger, showers in which a million or more electrons and positrons may sweep over an area of many square meters simultaneously. Some of these showers at their maximum point may extend over 100 meters square or more, and involve an energy of 10^{14}–10^{16} volts. The frequency of these events, which can be recorded by coincidence counters separated by tens of meters, and illuminated by cloud chambers so operated that we may look at the radiation passing at a random point between the counters, is very small, but is still immensely greater than any tertiary cascade radiation would explain. Whether there is a weak high-energy primary cascade component, or whether these high-energy gamma rays or electrons are occasionally produced in the collisions of a primary protonic component with matter in the earth's atmosphere, is for the moment not known. And on this point, as on so many others that have arisen in this discussion, theoretical ideas can be only a rather untrustworthy guide, since their application involves an extrapolation over the known range of validity of existing theory by a factor of about one hundred million.

It is perhaps appropriate to conclude this report without attempting to alleviate the impression of uncertainty, of adventure, and of an inevitable confusion. For that is likely for a long time to be a part of research in cosmic rays.

SCIENCE IN THE UNIVERSITY

By Members of the Faculties of the University of California



UNIVERSITY OF CALIFORNIA PRESS
BERKELEY AND LOS ANGELES
1944

UNIVERSITY OF CALIFORNIA PRESS
BERKELEY AND LOS ANGELES
CALIFORNIA

◆

CAMBRIDGE UNIVERSITY PRESS
LONDON, ENGLAND

PRINTED IN THE UNITED STATES OF AMERICA
BY THE UNIVERSITY OF CALIFORNIA PRESS